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Reconfigurable Aperture Decade Bandwidth Array

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I. Introduction

A variety of military systems employ multiple antenna apertures on a single platform such as a ship or an aircraft. In order to reduce cost and improve performance characteristics such as Radar Cross Section, it is desirable to combine multiple functions into a single aperture. Wide (10:1) bandwidth phased array antennas are needed to accomplish this goal. The current state of the art of broadband phased arrays is approximately 3:1 bandwidth, which is not adequate to support a wide range of applications such as RADAR, satellite communications, and electronic counter measures.

To satisfy multi-mission roles from a single aperture over a 10:1 bandwidth requires an array that can be quickly reconfigured to operate efficiently over sub-bands corresponding to the various application frequencies. Array reconfigurability includes the ability to select operating frequency bands for the radiating elements and reconfigure the aperture illumination function with electronic control of the feed network in order to create any required radiation pattern. The goal of this research is to develop and demonstrate a grating lobe free REConfigurable APerture Decade Bandwidth phased ARray (RECAP DBAR) using control devices. Because of their small size and superior electrical characteristics, MEMS (Micro Electro Mechanical Systems) switches are the device of choice [1]. This paper addresses the array architecture and the design of a radiating aperture that may be reconfigured to provide a tunable phased array with an effective 10:1 operating frequency bandwidth. An array design based on a TEM horn with a switchable ground plane is used to illustrate the important concepts. We discuss a canonical array design to cover a 60° conical scan volume over the 2-20 GHz frequency band.

II. Array Architecture

A decade bandwidth array imposes unique requirements that are not usually encountered in a narrow band design. The most fundamental array constraint is lattice spacing, which is limited to one-half wavelength at the highest frequency ($\lambda_H/2$) in order to avoid the appearance of grating lobes. Consequently, the lattice spacing at the lowest operating frequency is reduced to approximately $\lambda/20$. In a typical active array design each radiating element is driven by a T/R module, which includes a phase shifter, GaAs FET amplifier, low noise receiver and circulators to isolate transmit and receive channels. New array architectures are needed because it impractical to package 10:1 bandwidth components into a $\lambda_H/2$ unit cell.

Figure 1 illustrates two possible decade bandwidth array architectures. Both of these concepts treat a group of radiating elements at the low frequency band as a single *virtual element*. The *switched feed* architecture relies upon a broadband switch at each radiating element to select between a high and low frequency feed network. Each feed uses reduced bandwidth components (~3:1), and it is feasible to package the low frequency electronics behind the high frequency manifold in order to reduce congestion. However, this architecture is limited to dual band operation due to packaging constraints.

Figure 1b introduces the *virtual element* feed architecture in which the array is built in layers corresponding to frequency bands. The illustration shows a three-band configuration. Note that the same transmission line infrastructure is used for all bands, but components are subdivided into smaller bandwidth (2:1) units. The T/R modules are designed to pass out of band signals using either switches or filters The high frequency band components are near the radiating aperture while larger low frequency components are located in the sparsely populated region near the input. This reduces circuit congestion near the radiating aperture where the $\lambda_H/2$ element spacing imposes a constraint. The architecture can be extended to 2-D arrays by using a hybrid slat/tile construction. In the 2-D case, the second tier components control a 2×2 virtual element, the

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third tier a 4×4 virtual element, etc. Although the total number of components is greater than in conventional array architecture, each part is less expensive due to the smaller bandwidth and greater available packaging volume This architecture also offers the potential for a high instantaneous bandwidth feed. For example, if switched line phase shifters are used for the low frequency band, they may also function as true time delay units for the higher frequency bands.

III. Reconfigurable Apertures

Array radiating elements may be broadly classified as follows: (a) traveling wave structures, which radiate in the forward direction, and (b) bi-directional structures, which require a ground plane to control the backward radiation. Traveling wave structures include tapered slot "Vivaldi" antennas of various configurations and 'bunny ear" [2] elements. Bi-directional elements include dipoles, slots, and planar self-complementary elements such as spirals. TEM horns are not strictly traveling wave structures but do exhibit predominantly forward radiation over a broadband of operation Several of these elements have been investigated for the RECAP array. The Vivaldi type radiator has the advantages of not requiring a backing ground plane, wide bandwidth, and amenable to dual polarization packaging. Reconfigurble multigridded CP spirals have been considered, but size constraints dictated by array spacings results in a much narrower element bandwidth in the array environment than that achieved with isolated elements. An alternate planar structure is a two level dipole array consisting of two interspersed slightly greater than 3:1 bandwidth dipole arrays designed to yield 10:1 total bandwidth. Due to the resonant nature of the dipoles, MEMS switches are required in the elements themselves as well as in the tunable ground plane, which can be implemented either with multiple ground planes or high impedance (Hi-Z) surface. In this paper, one element and the key challenges it presents will be highlighted, i.e., the TEM horn with reconfigurable ground plane.

Arrays of TEM horn antennas are capable of broadband performance [3], [4]. However, scan blindness may occur when a ground plane is added behind the array to prevent back radiation[5]. This blindness is caused by a travelling wave mode similar to a parallel plate mode propagating between the horn plates and the ground plane. It was previously demonstrated that the scan blindnesscan be eliminated by reducing the length of the flare opening. However, this reduction in the structure's physical volume has the effect of suppressing the low frequency performance, reducing bandwidth. A possible solution to this dilemma is to use a switchable mid-wall ground plane as shown in Figure 2. It may be constructed as a wire grid with capacitive MEMS switches at the wire junctions. When the mid-wall's switches are open-circuited, the secondary ground plane is transparent, giving the array the depth needed for good low-frequency performance. When the mid-wall is short-circuited, the structure is shallower, preventing the scan-blindness that would otherwise limit the high-frequency performance.

We have validated the concept numerically using a periodic hybrid finite element code to calculate infinite array properties. The unit cell in Figure 2 is $\lambda_H/2 \times \lambda_H/2$. The total depth is λ_H, split equally in front of and behind the mid wall. The array unit cell structure includes a length of TEM transmission line leading from the horn apex back to the feed point just above the primary ground plane. As shown by the graph on the right side of Figure 2, preliminary results indicate that the array elements' active gain can be held to within 1 dB of the maximum unit cell gain over a 10:1 bandwidth.

Practical design of the TEM horn is currently under investigation. We are exploring ways to extend low frequency performance, including tailoring flare shape and size in conjunction with a dual layer switched ground plane. A promising design has emerged in which horns are fabricated with an injection molded plastic substrate. This offers low cost manufacturing and also provides a support structure for the switched grid array that relaxes electrical requirements for a thin, low dielectric constant substrate. A broadband balun is needed to transition from a practical feed circuit medium, such as microstrip, tobalanced twin line. Promising balun design concepts are being developed and will be evaluated in the infinite array model to insure that leakage or modes created by the structure do not cause a scan blindness condition.

IV. Ground Plane Design

Bi-directional radiators require a broadband ground plane to operate over a decade bandwidth. Ground plane designs can be categorized as either electric or magnetic depending whether the reflection coefficient is positive or negative. In either case, an ideal ground plane provides a constant reflection coefficient phase versus frequency over the entire band. Broadband designs involve multiple layers of resonant structures.

Previous investigations suggest that fundamental physical constraints such as Foster's Reactance Theorem limit attainable bandwidth to a discrete set of available bands. One way to enhance performance is to use MEMS switches in a periodic grid to adjust the reflection coefficient phase shift for any desired frequency band. Numerical modeling suggests that this is feasible for either electric or magnetic ground planes.

A switchable electric ground plane for the TEM horn array may be constructed using a tightly spaced ($\sim\lambda_H/10$) grid of wires connected by MEMS switches as illustrated in Figure 3. When the switches are closed, the grid functions as a continuous electric conductor. Alternatively, when the switches are open the wires between each junction behave as a small dipole. Thus, an incident plane wave passes through the grid with a relatively small fraction of reflected power. A metallic sheet is placed $\lambda/4$ beyond the switched grid, resulting in a two-state switchable ground plane. Plane wave scattering analysis of a single switched grid unit cell is used to identify the important design parameters. The grid spacing is a dominant factor in both the on and off states, while in the off (transmissive) state the substrate thickness, dielectric constant and switch capacitance are also important. Figure 3 illustrates the configuration and computed performance for a TEM Horn grid design on a 6 mil substrate with ε_r=3, switch off state capacitance of C=10fF and on state capacitance of C=1pF. Acceptable electrical performance is obtained throughout both frequency bands and a comfortable overlap region is provided for applications that may "straddle" the two available bands. The grid design concept described here may also be used as a building block component for a multi-layer broadband ground plane design.

A more compact package is obtained from an array with many narrowband sub-bands over the 10:1 bandwidth. Frequency selectivity is determined by the need for a ground plane a set distance away from the radiating element. The thumbtack high impedance electromagnetic surface concept [6] provides an innovative way to create a ground plane in a thin structure. The drawback to this design is the relatively narrowband performance. To use the concept for a wideband array, this narrowband limitation must be overcome. Broadbanding techniques that maintain a thin profile are being developed and analyzed with periodic finite element codes.

V. Conclusion

Array antennas using MEMs switches have the potential to provide reconfigurability needed to combine multiple functions into a single aperture. For example, a TEM horn array with switchable ground plane has been numerically demonstrated to provide the RECAP goal of a 10:1 effective bandwidth. Two different ground plane concepts have been computationally verified: a reflective/transmissive ground screen with integrated MEMS capacitive switches for the TEM horn and a modified high-impedance surface for planar elements. Future work involves combining the MEMS-switched ground plane consisting of substrate and cover layers required for environmental protection with the TEM horn model in the phased array code in order to verify that no deleterious dielectric effects are introduced. Also, finite array effects need to be addressed with finite array codes rather than the finite element infinite array codes used thus far. Ultimately a reconfigurable demonstration array is planned to validate the final design concept.

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References:

[1] C. Goldsmith, Z. Yao, S. Eshelman, D. Denniston, "Performance of Low-Loss RF MEMS Capacitive Switches," *IEEE Microwave Guided Wave Lett.*, vol. 8, pp. 269-271, Aug. 1998.

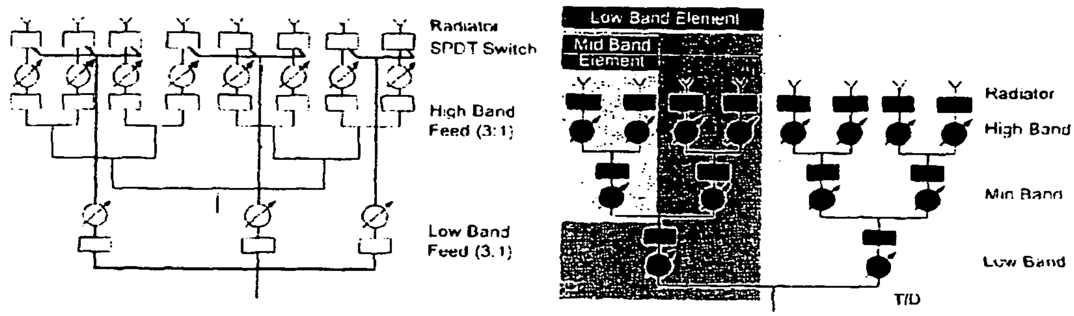
[2] J.J. Lee and S. Livingston, "Wide Band Bunny-Ear Radiating Element,", 1993 IEEE AP-S Symp. Dig., June 1993, pp. 1604-1607.

[3] C. Baum, "Some Characteristics of Planar Distributed Sources for Radiating Transient Pulses," SSN-100, AF Res. Lab., Kirtland AFB, NM, Mar. 1970.

[4] D. McGrath and C. Baum. "Scanning and Impedance Properties of TEM Horn Arrays for Transient Radiation," *IEEE Trans. Antennas Propagat.*, vol. 47, pp.469-473, Mar. 1999.

[5] D. McGrath, "Blindness Effects in Ground Plane-Backed TEM Horn Arrays," 1998 IEEE AP-S Symp. Dig., June 1998, pp. 1024-1027.

[6] D. Sievenpiper, L. Zhang, R.F. Jimenez Broas, N.G. Alexopolous, and E. Yablonovitch, "High-Impedance Electromagnetic Surfaces with a Forbidden Frequency Band," *IEEE Trans. Microwave Theory Tech.*, vol. MTT-47, pp. 2059-2074, Nov. 1999.



(a) Switched Feed Architecture

(b) Virtual Element Architecture

Figure 1. RECAP Array Feed Architectures

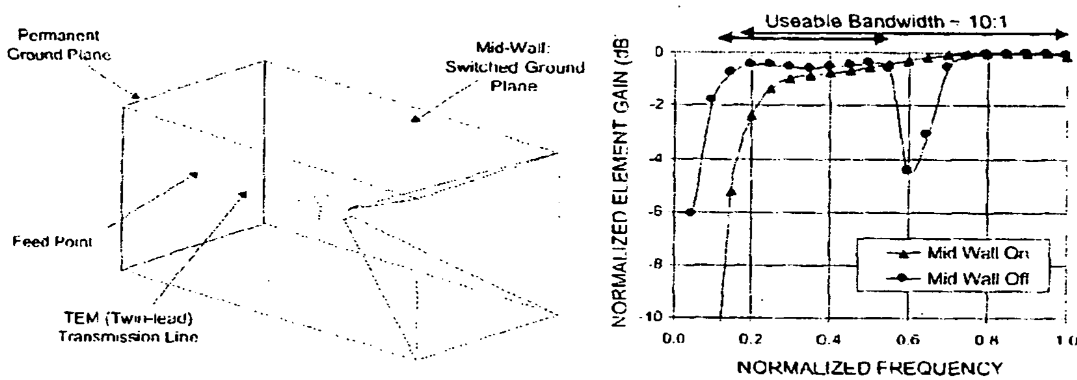


Figure 2. Left: Unit Cell for TEM Horn Radiating Element with Switchable Ground Plane; Right: Element Gain Relative to Maximum Unit Cell Gain at Broadside Scan

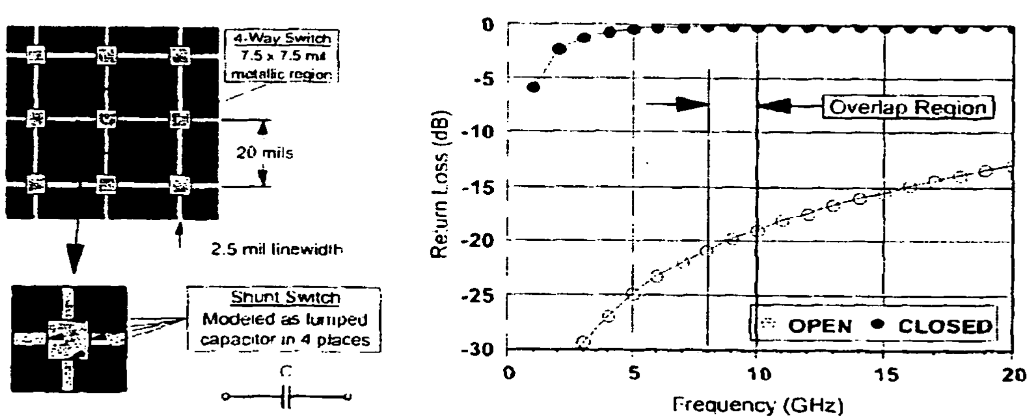


Figure 3 TEM Horn Switched Ground Plane Configuration with Broadside FSS Results